Investigating the Relationship between Fin Whales, Zooplankton Concentrations and Hydrothermal Venting on the Juan de Fuca Ridge

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LONG-TERM GOALS

We investigated the potential correlation between whale tracks, enhanced zooplankton concentrations and hydrothermal vents above the Juan de Fuca Ridge with the long-term goal of understanding the influences of globally distributed hydrothermal plumes on the trophic ecology of the deep ocean.

OBJECTIVES

We conducted a retrospective study using existing seismic and bio-acoustical data sets from the Juan de Fuca Ridge with the following objectives:

1. Developing an automatic algorithm to track fin whales using data from a small-scale seafloor seismic network.
2. Tracking vocalizing fin whales above the Endeavour segment in order to determine whether they are preferentially found above the hydrothermal vent fields where net tow and bio-acoustical data show that the zooplankton concentrations are higher at all depths.
3. Estimating the density of calling fin whales above ocean bottom seismometers deployed at mid-plate locations on the Explorer and Juan de Fuca plates and near the continental margin in order to test whether the density of vocalizing fin whales is unusually high around the Endeavour vent fields.
4. Analyzing >50 net tow samples from the Endeavour Segment from 1995-1996 to add to previously analyzed net-towed samples from 1991-1994. Using this data to calibrate

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simultaneous acoustic backscatter observations, and then combining net and acoustic data to constrain variations in zooplankton concentrations with depth and distance from the vent fields.

5. Using historical acoustic Doppler current profiler (ADCP) time series and ADCP data that will be collected by the NEPTUNE Canada cabled observatory to understand the relationship between the seasonal migration patterns of zooplankton and their enhanced concentrations within the water column above the hydrothermal vents.

APPROACH

The W. M. Keck Foundation supported an experiment on the Endeavour segment of the Juan de Fuca Ridge (Weekly *et al.*, 2013) that included a network of eight ocean bottom seismometers (OBSs) that operated from 2003-6. The experiment also included one-year deployments of OBSs on the Explorer plate and the continental slope offshore Nootka Sound (Fig. 1). More recently, NEPTUNE Canada has commenced seismic observations at 4 nodes on their cabled observatory including the Endeavour segment (Fig. 1). The OBS records include a very extensive data set of fin whale vocalizations. Previous work (e.g., McDonald *et al.*, 1995; Rebull *et al.*, 2006) has shown that seafloor seismic networks can be used to track fin whales but the data sets have been limited to a few tracks. Our approach to analyzing the Endeavour network data was to develop an automatic detection and tracking algorithm (Wilcock, 2012) that picks times of direct and multipath arrivals based on finding peaks in the instantaneous amplitude of the seismic records and uses a grid search approach to find the location that matches the observed arrival times best. The whale tracks can then be combined with calling patterns determined using a matched filter or spectrogram cross-correlation detector to investigate the behavior of vocalizing whales and their distribution relative to the vent fields. To determine call densities from call counts on single isolated OBSs requires a method to estimate the range of calls. To accomplish this we estimate the fin whale source levels using calls located with the Endeavour network and initiated the development of an automated technique to estimate the range of fin whales using the spacing and amplitude of multipath arrivals (McDonald and Fox, 1999).

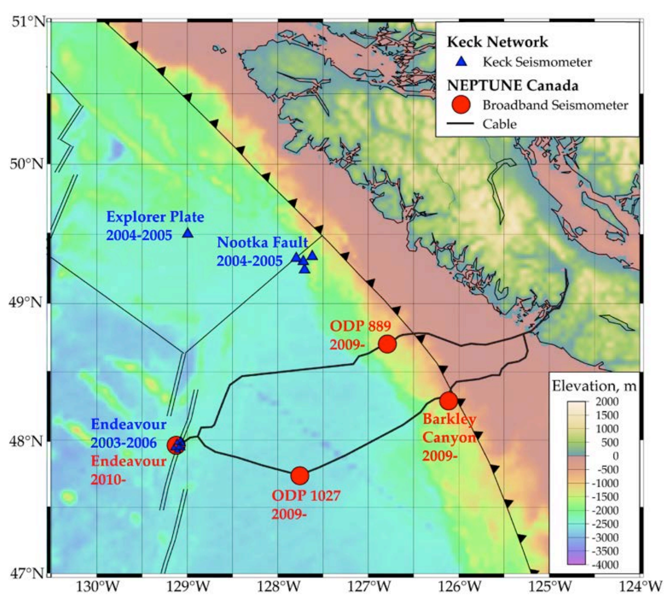

Fig. 1. Map of the NE Pacific Ocean off Vancouver Island showing the locations of seismometers deployed in the Keck experiment and broadband seismometers on the NEPTUNE Canada cabled observatory.

In the early to mid-1990s, the Institute of Ocean Sciences in Sidney, BC conducted summer cruises to the Endeavour to collect a series of plankton net tows in conjunction with measurements including acoustic backscatter intensity (Fig. 2). The prior analysis of net samples collected in 1991-4 shows enhanced zooplankton concentrations at all depths above the hydrothermal vent fields (Burd and Thomson, 1994, 1995). At depth, the zooplankton are concentrated in a layer of increased acoustic backscatter near the top of the hydrothermal plume (Thomson *et al.*, 1991; Burd *et al.*, 1992), leading to the inference that the zooplankton are grazing on the plumes. Community analysis shows that the deep faunal assemblages above the vents are infiltrated by shallow species, which presumably migrate vertically between the upper ocean and the hydrothermal plume (Burd and Thomson, 1994, 1995). Our approach is to analyze additional net samples collected in the area from 1995-6 to identify major zooplankton and fish species and determine length, gender, stage of development, and dry/wet biomass. The expanded zooplankton data set can be used to refine our understanding of variations in zooplankton concentrations with distance from the hydrothermal vent fields. The data on zooplankton distribution and biomass in the water column overlying Endeavour Ridge are well suited to acoustic calibration of net samples because the ADCP was mounted just below the multiple-net apparatus and the attitude sensors and current measuring capabilities of the ADCP allowed us to determine the flow volume with only 2 to 3% error (Burd and Thomson, 1993). A close regressional relationship between the biomass and acoustic backscatter (for the specified scattering cross-sectional model) means that profile acoustic data can be used to map three-dimensional distributions of biomass in the vicinity of the ridge without the need for expensive and labor intensive net sampling tows. The relationship can be used to interpret upward looking ADCP data collected in the Axial Valley with autonomous instruments deployed from 2003-6 and with the NEPTUNE Canada cabled observatory starting in 2010.

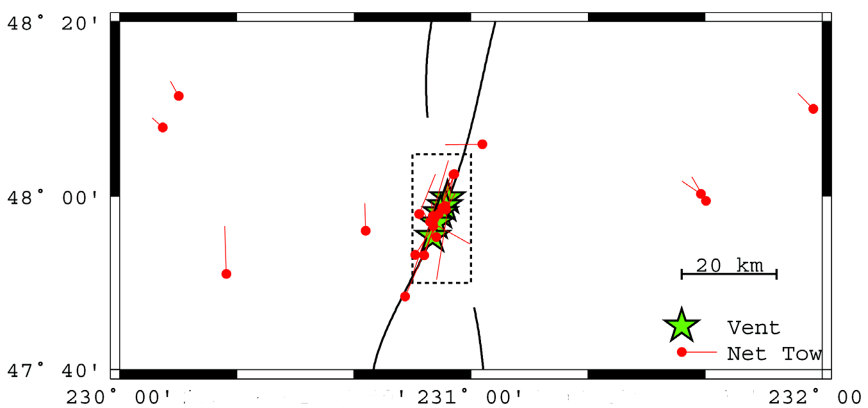

Fig. 2. Regional map showing the location of the Endeavour vent fields (green stars), ship tracks for net tows in 1991-1996 (red line with a red circle at the start of the track), the location of the spreading ridge axis (solid line) and the area covered by Figure 1 (dashed line).

WORK COMPLETED

We completed the following work to address our five objectives:

1. We developed an automated detection and tracking algorithm for fin whales and demonstrated a technique to improve the relative locations of nearby calls on a track (Wilcock, 2012).

2. We obtained >150 fin whale tracks with a total duration of ~800 hours in and around the Keck Endeavour seismic network and analyzed these for call characteristics, calling patterns, swimming patterns, net seasonal migration, diurnal variations and density of calling whales (Soule and Wilcock, 2013).

3. We obtained fin whale call counts at the Endeavour and several other instrumented locations (Weirathmueller *et al.*, 2011), measured the source amplitude of fin whales (Weirathmueller *et al.*, 2013) and developed a technique to range to fin whales based on the spacing and amplitudes of multipath arrivals (Weirathmueller and Wilcock, 2013a, 2013b).

4. We analyzed all net samples collected in 1995-6 during towed ADCP/CTD/Optics/Tucker trawl surveys near Endeavour Ridge to add to a 1991-4 historical database. We used simultaneous acoustic backscatter and net tow data to obtain a calibration of the acoustic observations (Burd and Thomson, 2012) and we estimated total water column biomass and secondary production from net- and acoustic-derived data for a broad region centered on the Endeavour vent fields (Burd and Thomson, 2014).

5. We have examined upward looking ADCP data for seasonal variations in deep scattering layers but this work has been hindered by extensive delays in the installation of moored instrumentation on the NEPTUNE Canada cabled observatory.

RESULTS

1. *Fin Whale Tracking Algorithm.* The algorithm (Wilcock, 2012) detects fin whale calls based on their amplitude and frequency content and picks arrival times for direct and multipath arrivals at local maxima of the smoothed instantaneous amplitude. Locatable calls are identified by searching for nearly coincident arrivals on multiple ocean bottom seismometers. A grid search algorithm is used to systematically search for the location that provides the best fit to the arrival time data with no prior assumptions about whether the first picked arrival time on a station is a direct path or a multipath. With some minimal user intervention tracks can be reliably obtained to distances of 10-15 km outside the network (Fig. 3). Amplitude and particle motions can be incorporated as additional constraints but for the Endeavour network do not improve the quality of locations. Waveform cross-correlation and the double difference method (Waldhauser and Ellsworth, 2000), provides a useful means to improve fin whale tracks yielding locations relative to nearby calls that are accurate to a few tens of meters within the network (Fig 4).

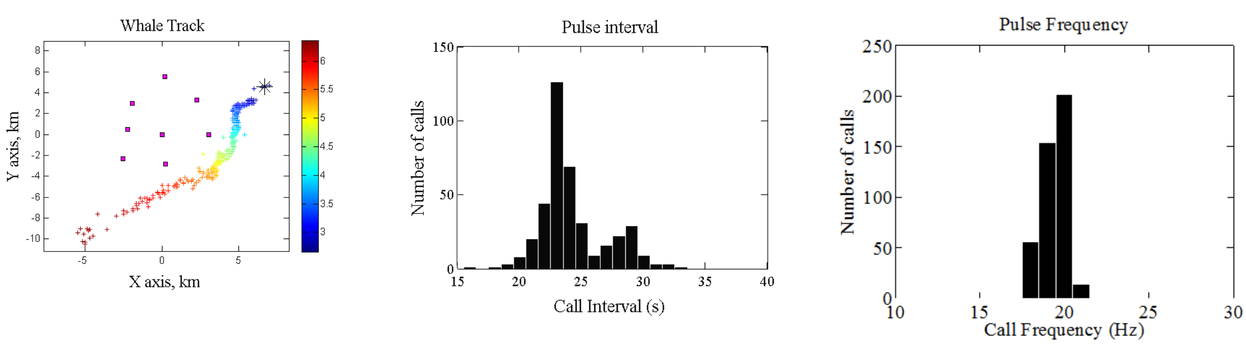

Fig. 3. (Left) Example of a dual 25/30 IPI track for February 4, 2004. The network is shown by purple boxes and the track by crosses color coded by time of day. Over 4 hours the whale swims from east of the network to the southwest. (Center) Histogram of pulse interval showing peaks near 25 s and 30 s. (Right) Histogram of call frequency showing a peak near 20 Hz.

2. *Fin Whale Tracks.* The fin whale call sequences are observed from August through April and the tracks can be classified into 4 categories based on the inter pulse interval (IPI): (1) simple 25 s IPI tracks, (2) 25/30 s dual IPI tracks, (3) 13/25 s dual IPI tracks and (4) complex IPI tracks in which the IPI ranges from <5 s to ~30 s and shows no clear pattern (Soule and Wilcock, 2013). From August to October the complex IPI tracks are the most common and these are predominantly directed northward (Fig. 5). The simple IPI tracks are the most common track in November and the 13/25 s dual IPI tracks are most common in December but the dual 25/30 s IPI tracks dominate total track count from November to March (Fig. 5). These tracks all have a weaker tendency to be oriented southwards. Although our dataset only covers a very small area the net directionality is inconsistent with the commonly observed pattern of baleen whale migration in which whales head north in the spring and south in the fall (e.g., Payne and Webb, 1971; Mizroch *et al.*, 2009). The complex IPI tracks that include many higher frequency calls may be pods of juvenile males that are headed north in the fall. The simple and dual IPI calling patterns are generally attributed to breeding males (Watkins *et al.*, 1987; Croll *et al.*, 2002) are consistent with whales moving slowly southward over the winter before migrating north silently in the Spring.

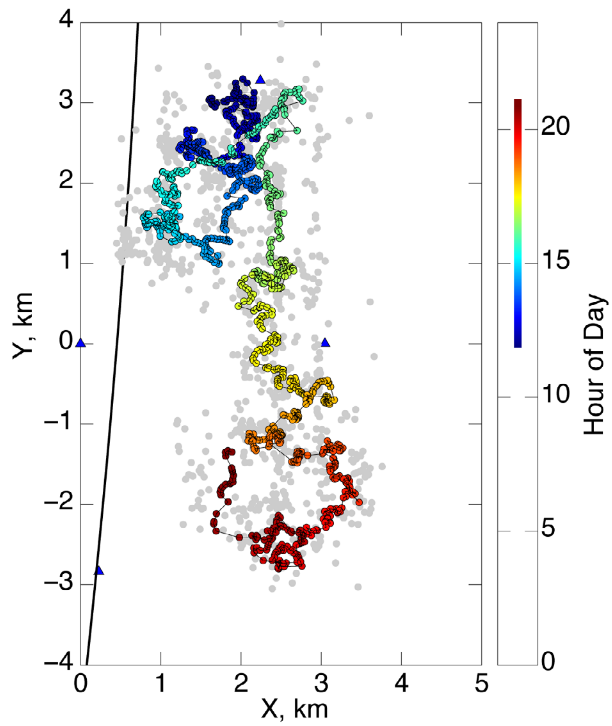

Fig. 4. Example of a track with the seismic network located with the automated grid search method (grey circles) and then refined with cross-correlation and the double-difference method (circles colored by time). The ridge axis is shown by a black line and OBSs by blue triangles.

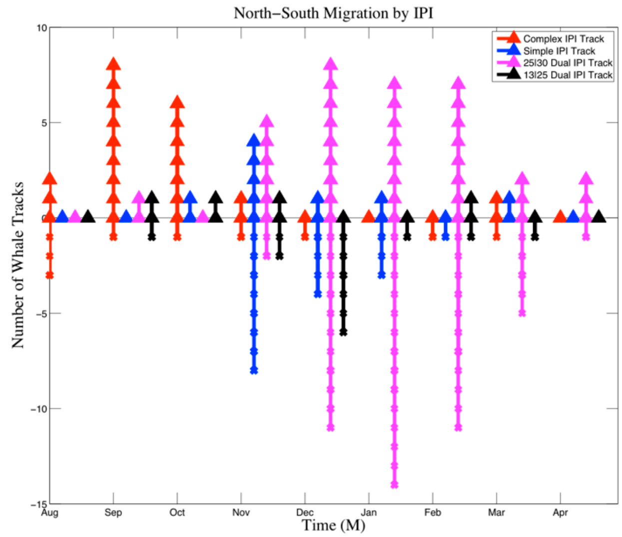

Fig. 5. Distribution of tracks types by month with tracks moving form north to south plotted on the positive Y-axis and track moving from south to north plotted on the negative axis. Complex IPI tracks occur predominantly in the fall and move northwards while the simple and dual IPI tracks are predominantly in the winter and have a slight tendency to move southward.

The distribution of fin whales around the network is non-random with more calls near the network and to the east and north (Fig. 6). The mean near surface currents in the region are characterized by flow to the east and northeast associated with the Eastward North Pacific Current (Strub and James, 2002). This distribution is consistent with a higher density of calling whales in a region where a food source near the hydrothermal vents that has been advected by the ocean currents. A more definite test of the linkage between hydrothermally-supported zooplankton and fin whales would require measurements of zooplankton concentration in the winter and a better understanding of the linkages between vocalizing whales and whales feeding in the vicinity.

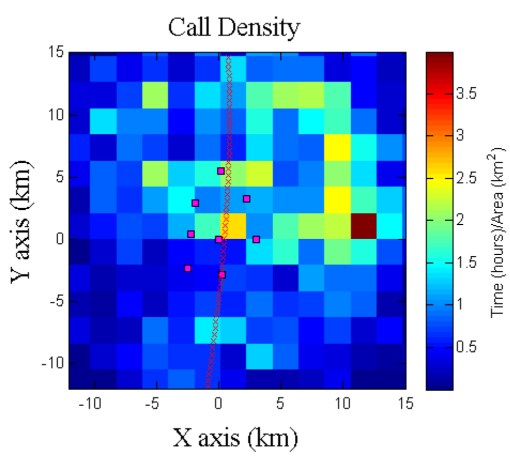

Fig 6. Density of calling whales in units of hours per kilometer squared. The highest densities are observed to the east and within the network and the lowest to the southwest.

3. *Comparing Fin Whale Call Densities Between Sites.* Histograms of call counts (Fig. 7), that have been adjusted to account for different background noise levels for 2004-5 from the Endeavour, Explorer Plate and Nootka Fault sites, show that the call count is lower at the Endeavour than the other two sites (Weirathmueller et al., 2011). However, without additional analysis it is unclear whether this is an effect of enhanced propagation in the smooth sedimented sites of the Explorer Plate and Nootka Faults compared to the rough volcanic bathymetry of the Endeavour or if it indicates that whale densities are lower near the Endeavour vent fields.

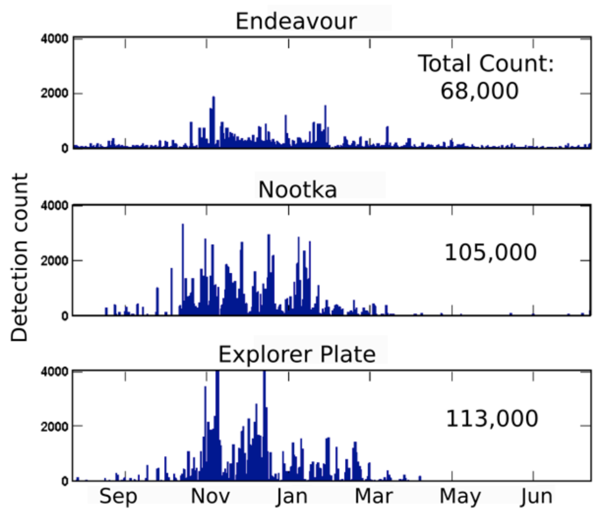

Fig 7. Histograms of daily fin whale call counts for the Endeavour, Nootka and Explorer plate sites for 2004-5. The detections have been normalized to a uniform background noise level. Detections are highest between November and March at each site and the total number at the Explore and Nootka sites is almost double that at the Endeavour.

Since single station methods for locating whales benefit from knowledge of source amplitudes we determined the source amplitudes of fin whales (Weirathmueller *et al.*, 2013). We obtained an average source level of 189.9 ± 5.8 dB re 1uPa @ 1m from a total of 1241 calls in good agreement with another recent study in the Antarctic (Sirovic *et al.*, 2007). The variation in estimated call intensity can be largely explained by a uniform source level coupled with horizontal and vertical uncertainties in the source location (Fig. 8); in particular variations in calling depth can lead to significant apparent amplitude variations due to interference between the direct and surface reflected arrivals.

The automated method to obtain ranges to whales using multipath arrival times (Weirathmueller and Wilcock, 2013a, 2013b) and amplitudes at a single OBS presently works reasonably well for calls up to ~8 km in water depths of 2-2.5 km (Fig. 9), but challenges remain eliminating more distant calls that are erroneously placed at shorter ranges. There is also a tendency for calls within a horizontal distance of 2-3 km from the OBS calls to be located near the receiver. We are presently embarked on a project that will further develop this technique and compare and validate it with other ranging techniques for single OBS (Harris *et al.*, 2013; Mellinger *et al.*, 2009) – a technique that combines different methods may be the best approach.

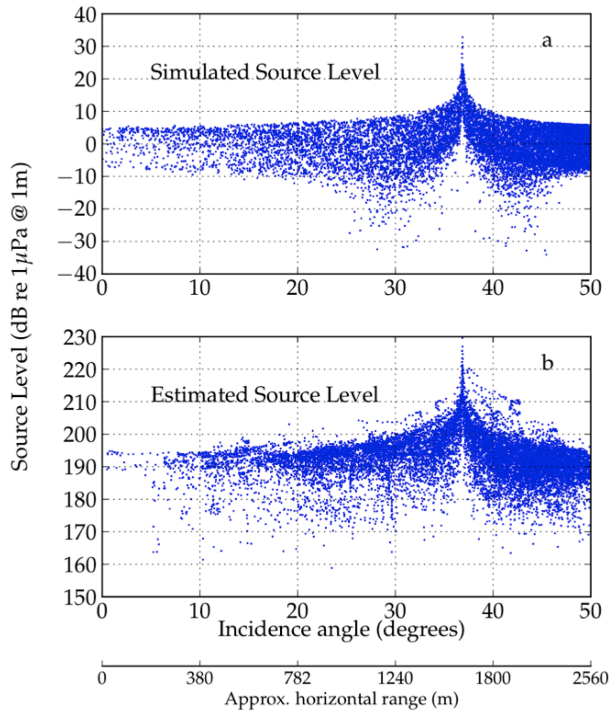

Fig 8. (a) Model source level output for an input source level of 0dB. (b) Source levels estimated from data. Both are plotted versus incidence angle, but a second X-axis shows approximate range for a call generated at 50 m depth and a total water depth of 2200 m.

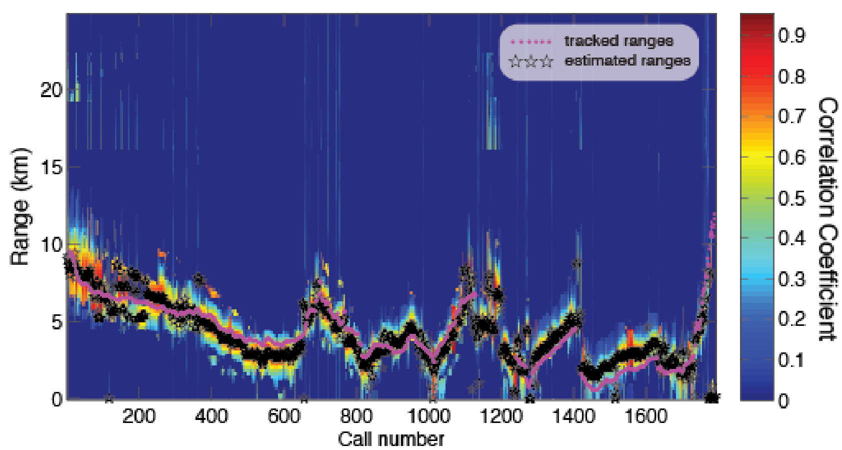

Fig 9. Range estimated using multipath spacing and amplitude for a series of fin whale calls in December 2003. Colors in the image indicate correlation on a scale from 0-1, with 1 being a perfect match. The maximum of each vertical slice corresponds to the closest match between measured multipath arrival and range model, and is annotated with a black star. Magenta dots show ranges from previously estimated call locations.

4. *Net Sample and Backscatter Analysis.* We used simultaneous acoustic backscatter and net tow data from 1991-6 to obtain a calibration of the acoustic observations based on 197 mixed-species zooplankton net samples collected during the summers of 1991-6. Using the observed acoustic volume scattering strength referenced to the regional background scattering strength for the depth range 1000

to 1400 m known to have with very few animals and highly accurate flow volume measurements for the nets, we find that the acoustic backscatter signal accounts for 84% of the variance in the net biomass data (Fig. 10). Results are unaffected by organism size, daily migratory patterns, or depth range. Burd and Thomson (2012) discuss the potential use and limitations of this approach in broad-scale, full water-column studies of secondary production in the vicinity of the Endeavour Ridge vent region.

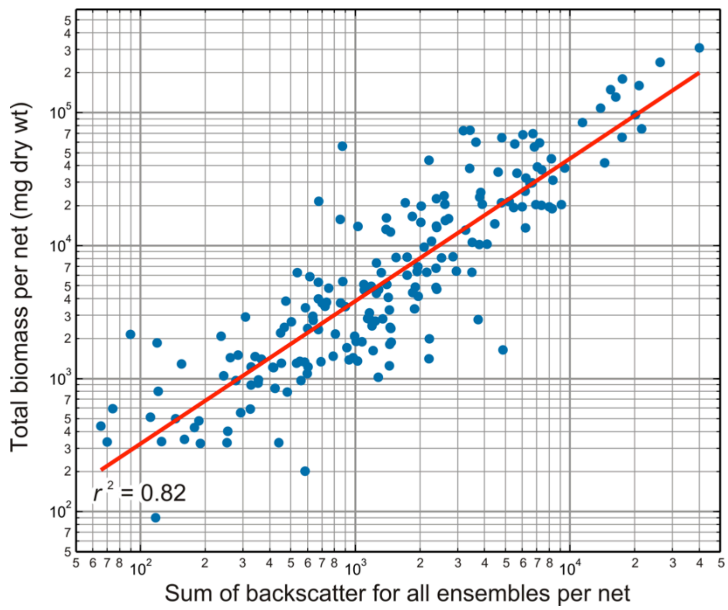

Fig. 10. Log-log scale linear regression of total net biomass versus sum of target strength over all acoustic ensembles (Burd and Thomson, 2012). The regression predicts 84% of the variance in the data.

A combined analysis of net and acoustic data for water column biomass and secondary production (Burd and Thomson, 2014) reveals statistically significant exponential decline in total water column biomass with increasing distance from vent fields (Fig. 11). The net-calibrated acoustic backscatter data show a similar decline, but only below 800 m depth (Fig. 12). Near-surface biomass was highly variable throughout the region, but values near vents consistently ranged higher than summer values found elsewhere in the open North Pacific. Water column biomass was similar in magnitude above and below 800 m depth throughout the region, suggesting that open ocean studies limited to sampling depths less than 250 m are missing a large fraction of the zooplankton biomass and production in the open ocean. Because currents can advect epiplume biomass a considerable distance from the vent fields, biomass enhancement of the water column in the vicinity of Endeavour Ridge may extend a considerable distance to the west and northwest of the vent fields in the direction of the prevailing subsurface flow.

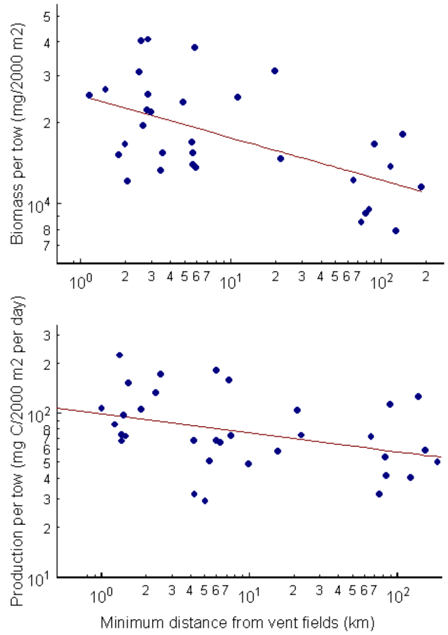

Fig. 11. Total water column biomass from net tows (integrated over the depth range 0-2000 m) measured relative to distance from the main Endeavour vent fields.

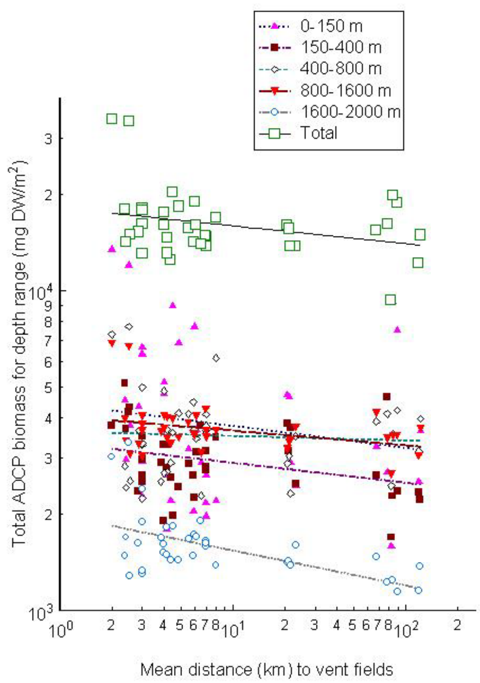

Fig. 12. Depth stratified water column biomass relative to the distance from the main Endeavour vent fields. Values are estimated from the net-calibrated acoustic backscatter data.

5. *Seasonal variations in backscatter intensity.* Extensive work has been conducted on the biomass, production and spatial distribution of summer epiplume scattering layers (1500-1900 m depth) found near the hydrothermally active vent fields of the Endeavour Ridge. Until now, there has been insufficient data to determine if these deep scattering layers are a seasonal phenomenon related to ontogenetic migrations of upper ocean fauna, or if they are a persistent, year round assemblage. If the former, how do these layers migrate, and when are they most intense?

Two moorings within the Ocean Networks Canada NEPTUNE array were active from 2010 to 2012. The moorings are situated 600 m from one another across the axial valley (Fig. 13), each with an upward-looking 75 kHz acoustic Doppler current profiler (ADCP). Fig. 14 presents a set of waterfall plots showing mean-averaged (over 1 full year) depth distributions of acoustic anomalies for the NE mooring. We had hoped to use more recent NEPTUNE data to more clearly define the seasonality of deep scattering layers in the Endeavour Ridge venting region. However, due to major cable failures, infrastructure problems, and lack of ship time, the moored instruments have gone dormant and are no longer providing data. We have, therefore, changed course and are presently beginning to examine acoustic ADCP records previously collected in the region. This has considerably delayed the completion of this part of our investigation, which we hope to complete once an additional year or more of acoustic backscatter data has been recorded by the NEPTUNE ADCPs.

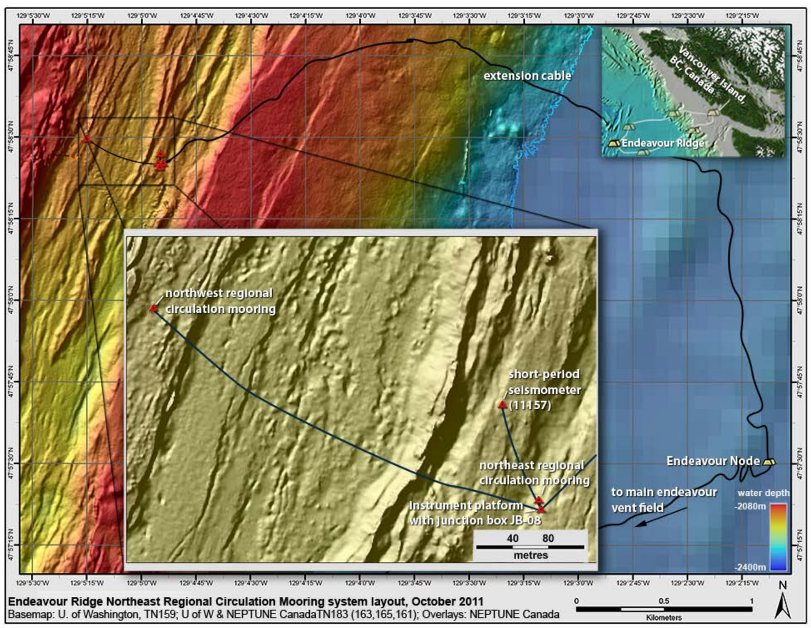

Fig. 13. Location of the two Ocean Networks Canada moorings to the NE and NW of the main Endeavour Ridge axial valley. The moorings are still in place but are no longer connected to the cabled observatory.

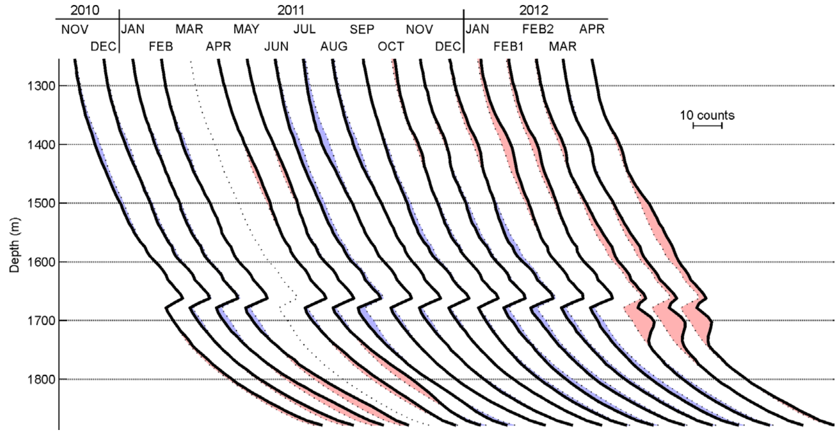

Fig. 14. Monthly mean acoustic backscatter intensity profiles from the Axial Valley showing backscatter anomalies relative to the annual meanprofile. Anomalies are positive (red) and negative (blue) over the depth range covered by the transducers. The height-above-bottom attenuation of the signal (converted to actual depth) is due to signal loss with distance from the upward looking ADCP moored at 250 mab.

IMPACT/APPLICATIONS

We have built upon earlier studies that utilized seismic networks to obtain a few whale tracks to demonstrate that automatic fin whale detection, location and ranging algorithms that can be applied to seafloor seismic networks understand the distribution and behavior of fin whales. The location and ranging algorithms could be adapted to other vocalizing species (or anthropogenic sounds) recorded by a network of seafloor receivers provided the calls are sufficiently short and spaced far enough apart so that the direct and multiple arrivals do not overlap. The double difference method is commonly used in earthquake studies but has not previously been applied to marine mammals. The close relationship between biomass and acoustic backscatter provides a method to extrapolate limited net tow data to images of the 3-D distribution of biomass and has been used to infer that secondary production is enhanced by the hydrothermal vent fields. If a correlation if found between the distribution of whales, enhanced zooplankton concentrations and hydrothermal vents it will have implications for our understanding of the global influences of hydrothermal vents on the trophic ecology of the ocean.

RELATED PROJECTS

The Endeavour node on Ocean Network Canada's NEPTUNE Canada regional cabled observatory (http://www.oceannetworks.ca/installations/observatories/northeast-pacific/endeavour) will, when fully implemented, include a water column experiment that will monitor deep macrozooplankton concentrations (Rick Thomson is the lead-PI) and a seafloor seismic network (William Wilcock is a co-PI). The amphibious portion of Cascadia Initiative is an ambitious NSF project that is deploying 70 OBSs from 2011-2015 at ~160 sites over the Juan de Fuca plate and Cascadia margin from approximately 40°N to 50°N, thus providing the opportunity to investigate the broader spatial and temporal distribution of fin and blue whales. Wilcock has a collaborative ONR-funded project (N00014-14-1-0423) with David Mellinger at Oregon State University to investigate fin and blue whales with this data set and in particular develop and compare density estimation techniques.

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